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We developed algorithms for cooperative search and attack of targets by smart munitions such as the Low Cost Autonomous Attack System (LOCAAS). We considered 4 or more munitions attacking a single target whose location was unknown and hidden among decoys. We assumed the munitions had a constant airspeed and maintained a constant altitude while performing a systematic search for the target in the presence of atmospheric winds. After one of the vehicles finds a target, the other vehicles are notified and one is tasked with obtaining a second independent sighting from a different angle of observation. After confirmation by the second vehicle, the target is attacked.

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ROBUST FLIGHT CONTROL
Final Report

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January 2000 through December 2002

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Introduction

The objective of the three-year project was to develop advanced control for single vehicles and multiple cooperative vehicles. In the first year of the effort we focused on the control of a single under-damped vehicle with a saturating actuator. In the second year we focused on cooperative search with flight vehicles that had constant non-zero velocity and constant altitude. In the third year we extended our cooperative search approach to hovering vehicles with collision avoidance at constant altitude where the obstacles were tall buildings in an urban setting.

Year 1 Accomplishments

We defined a systematic procedure for designing the control laws using both time optimal control and dynamic inversion control. We applied the procedure to a fourth order model of the X-38 lifting body lateral-directional dynamics.

Our approach consisted of developing a reduced order model, developing the time optimal switching function, defining the ellipse for transition between time optimal and linear control, and defining the linear control law.

A reduced order model was developed that consisted of two second order systems with a control input variable for each of the lightly damped oscillators. We made an approximation at this step which was reasonable for the X-38 flight condition we selected.

The time optimal control of an under-damped oscillator is documented in textbooks and we applied the known results to our case of two under-damped oscillators each with its own independent control actuation input. In the time optimal control problem the solution that minimizes the time to the origin for a bounded input is a bang-bang type of control. We derive a switching function in the state space for when to change from a maximum control to a minimum control.

Next we developed an ellipsoid in the state space which was used to determine whether to use linear control (when inside the ellipse) or time optimal control (when outside the ellipsoid). This ellipsoid was selected by eye-ball and not formally developed with the LMI methodology we had planned because our efforts in this program were re-directed towards cooperative control of multiple vehicles.

The control law for the second order system worked as expected and is documented further in Reference 1.

Year 2 Accomplishments

We developed algorithms for cooperative search and attack of targets by smart munitions such as the Low Cost Autonomous Attack System (LOCAAS). We considered 4 or more munitions attacking a single target whose location was unknown and hidden among decoys. We assumed the munitions had a constant airspeed and maintained a constant altitude while performing a systematic search for the target in the presence of atmospheric winds. After one of the vehicles finds a target, the other vehicles are notified and one is tasked with obtaining a second independent sighting from a different angle of observation. After confirmation by the second vehicle, the target is attacked.

Our approach consisted of three basic elements.

- We used a basic maneuver as a fundamental building block for trajectory generation.
- A task assignment algorithm was developed to assign individual tasks to the group of vehicles performing a cooperative search mission.
- Dynamic inversion was used to develop control laws for each vehicle to track the trajectory commands in the face of atmospheric wind disturbances.

The purpose of the path generation is to find the shortest path starting with the initial condition of the vehicle and ending up on the straight line over the target with the specified target heading. We construct such a path with two arcs and two line segments as discussed in Reference 2. The cumulative length of these paths is used for task assignment.

In the second element of our approach we optimally determine the task assignments using path length (which for constant velocity is proportional to the time needed to complete the maneuver) as the cost function. Task assignments are re-determined whenever any vehicle completes a task. If we assume there are an equal number of tasks and vehicles there are n! possible ways to assign tasks. For our case, $n = 4$ and we examine all 24 possibilities and select the assignments that correspond to the smallest total cost.

The paths (from the path generation step) are passed to the appropriate vehicles (determined in the assignment step) as commands to the vehicles' control algorithms. The control law consists of an inner and outer loop. The inner loop receives inputs from the command generator based on the basic maneuver discussed above. The outer loop forms the distance between the vehicle and the commanded path and computes a heading command to track the commanded trajectory.

The path generation, task assignment and control law were tested for several search patterns and are documented further in References 2-4.

Year 3 Accomplishments

When an obstacle is detected, the commanded flight path is changed to avoid a collision. We have considered two levels of obstacle avoidance. The first level is a planning level which modifies or inserts waypoints that define the commanded path. The other level is a control level where we ignore the commanded path to avoid hitting an obstacle. In the ideal situation, where we have perfect knowledge of the obstacles, vehicle position measurements and no wind disturbances, only the planning level is required to avoid collisions. In non-ideal situations, the control level is used to avoid collisions that were not prevented by the planning level.

At the planning level, we start with a set of waypoints and a path where collisions with obstacles may occur if the path is followed. If we find waypoints *inside* obstacles we move them to a pre-determined points outside of the obstacle. When the path intersects an obstacle, but the waypoints (at each end of the path) are *outside* the obstacle, then we insert waypoints. After waypoint replacement/insertion in the planning level we have a new set of waypoints and a path-plan that avoids collisions with the known obstacles.

At the control level, in the event that the vehicle approaches to within a safe distance of an obstacle while tracking the commanded trajectory, we intentionally modify the vehicle commands to stay outside of a buffer zone around an obstacle. This could involve turning the trajectory away from the obstacle and/or braking of the vehicle as necessary. The control level is necessary since the obstacle data base used in the planning level may be incomplete or inaccurate.

The collision avoidance planning and control levels were integrated with our cooperative search algorithms from the previous year's research. We analyzed the performance of the algorithms for single vehicles and with multiple vehicles performing a cooperative search in a urban environment. More detailed results are available in Reference 3.

Personnel Supported
Dale Enns, Dan Bugajski, and Steve Pratt from Honeywell Laboratories.

Transitions
The robust flight control has been transitioned to the Organic Air Vehicle (OAV) program. This is a DARPA sponsored program which is developing technology

development for Future Combat Systems which is a U.S. Army program. The control laws for the OAV program include dynamic inversion based outer loops for controlling the trajectory as was used in our AFOSR research. Software for the path generation of multi-vehicles and collision avoidance developed in this AFOSR funded research is currently being integrated with the OAV control software and avionics hardware.

References

1. Enns, D.F., "Robust Flight Control for Aircraft With Saturating Actuators," F49620-00-C-0003, AFOSR Progress Report, 1 August 2000.

2. Enns, D.F., "Guidance and Control for Cooperative Search," F49620-00-C-0003, AFOSR Progress Report, 18 June 2001.

3. Enns, D.F., "Navigation in the Presence of Known Obstacles With Application To Cooperative Search," F49620-00-C-0003, AFOSR Progress Report, 1 August 2002.

4. Enns, D.F., D.J. Bugajski and S.G. Pratt, "Guidance and Control for Cooperative Search," American Control Conference 2002, Anchorage, Alaska, May 2002.

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